Attorney Docket: 2229/134

Metering Fuel Pump

The present application is a continuation-in-part of U.S. Patent Application ser. no. 09/853,239, filed 5/11/01, atty. docket 2229/119, which is a continuation-in-part of U.S. Patent Application ser. no. 09/517,686, atty. docket 2229/112, filed 3/2/2000. The present application is also a continuation-in-part of U.S. Patent Application ser. no. 10/361,354, filed 2/10/03, atty. docket 2229/144, which is a divisional application of U.S. patent application, no. 09/883,077, filed 6/15/2001, atty. docket no. 2229/118. All of the preceding applications are incorporated herein by reference in their entirety.

Technical Field

The present invention relates to metering fuel pumps for pressurized combustion chambers.

Background

Engine burners, such as those used in Stirling engines, have one or more heat exchangers that produce significant back pressure at the air and fuel injection points. This back pressure can exceed 0.5 pounds per square inch gauge ("PSIG"). Gaseous fuels in most buildings and homes are supplied at pressures well below 0.5 PSIG. A fuel pump in the gas supply train may be used to raise the fuel pressure high enough to allow efficient mixing with of fuel with air. Prior art engines include some type of valve or throttle plate or other restrictive device to meter fuel into a combustion chamber. This restrictive device adds to the parts count and complexity for these engines. Elimination of such restrictive devices would simplify engine design.

Summary of the Invention

In an embodiment of the present invention, there is provided a system for controlling the flow of a gaseous fuel from a fuel supply into a pressurized combustion chamber. The system includes a pump whose inlet is connected to a fuel supply. The pump outlet is connected to the combustion chamber. A chamber controller signal modulates the pump's

action to control the fuel flow to the chamber. The controller signal may be based on a sensor that monitors an operating parameter of the system containing the chamber. The controller can, for example, maintain a head temperature constant, where the pressurized chamber is part of an external combustion engine. The controller may also maintain a fuel/air mixture ratio for the burner at a constant value. The pump may be a piston pump or a diaphragm pump driven by linear motors. The pump may also be a rotary pump such as a vane pump or a crank–driven diaphragm pump. The controller signal may be an alternating current signal that varies in amplitude to control the fuel flow. Alternatively, the controller signal may be a pulse-width-modulated direct current signal. The signal duration or frequency or both may be varied to control the fuel flow to the chamber. Alternatively, the controller signal may control the speed of a rotary pump. The speed of the rotary pump may be actively controlled using a speed sensor, tachometer or the back-EMF on the windings.

The system may be used advantageously to both control the fuel flow and increase the pressure of the gas supplied to the combustion chamber. The system advantageously eliminates the throttle plate or valve or other restrictive device that is used to control the flow of fuel to the chamber in prior art systems.

Brief Description of the Drawings

The foregoing features of the invention will be more readily understood by reference to the following detailed description, taken with reference to the accompanying drawings, in which:

Fig. 1 is a block diagram showing a system for controlling a pressurized combustion chamber of an engine according to an embodiment of the present invention;

Fig. 2 shows a piston pump according to an embodiment of the invention;

Fig. 3 shows an alternating current waveform suitable for driving the piston pump of fig. 2;

Fig. 4 shows a pulse-width-modulated direct current waveform suitable for driving the piston pump of fig. 2, according to an embodiment of the present invention;

Fig. 5 is schematic diagram of a diaphragm pump according to an embodiment of the present invention;

Fig. 6 is a schematic diagram of a center-tapped coil for a diaphragm pump according to an embodiment of the present invention;

Fig. 7A-B shows pulse-width-modulated direct current waveforms suitable for driving the center-tapped coil of fig. 6, according to embodiments of the present invention; and

Figs. 8A-8D show embodiments of the invention that include a filter between fuel pump and combustion chamber.

Detailed Description of Specific Embodiments

The fuel flow to a pressurized combustion chamber may be metered by varying the operating parameters of a fuel pump. Desired performance may be achieved without the throttle plates or valves or other restrictive devices that are normally used to meter the fuel flow to the combustion chamber.

Fig. 1 shows a metering pump system providing gaseous fuel to a pressurized combustion chamber **58** of an engine **22** according to an embodiment of the invention. A gas train, labeled generally as **5**, includes a fuel pump **14**, interconnecting lines **38, 42** and may include a pressure regulator **18**. The fuel pump **14** raises the fuel pressure in line **38** to a higher pressure in line **42.** The gas train delivers fuel from the gas supply to the burner **10**, where it is mixed with air and burned in a combustion chamber **58**. The fuel pump is controlled by a controller **34** that modulates the fuel flow rate by varying one or more parameters of an electrical signal sent to the fuel pump **14**. The controller may also regulate a blower **60** that provides air to the combustion chamber **58** and may receive signals from sensors that report engine-operating parameters.

In an embodiment of the invention, the delivered fuel pressure in line **38** is 6 to 13 inches water column for liquefied petroleum gas. Natural gas may be supplied in line **38** at even lower pressures of 3 to 8 inches water column. Alternatively, pressure regulator **18** can supply the fuel at lower pressures, even negative pressures. Typical fuel pressures in line **42** may range from 0.5 to 5 PSIG.

In a preferred embodiment of the invention, fuel pump **14** is a linear piston pump. A linear piston pump is shown in fig. 2. The pump includes a cylinder **100**, a piston **102**, a winding **104,** a spring **106** and check valves **108, 112**. When an electrical signal is applied to winding **104,** the winding pulls the ferrous metal piston **102** to the left, compressing the spring **106**. Check valve **108** in the piston allows fuel to flow into compression volume **110**. When the electrical signal is turned off and the electromagnetic force on the piston begins to

decrease, the piston **102** is forced to the right by the spring **106.** Gas is forced out check valve **112** into the receiver volume **114** at a higher pressure.

The flow rate of the pump can be modulated by varying the stroke of the piston **102**. In one embodiment of the invention, the signal from the controller to the pump is a half-wave alternating current ("AC") signal, as shown in fig. 3. Circuitry to produce this signal is well known in the art. The piston stroke and, thus, the flow rate increases as the amplitude of the AC signal increases. In a preferred embodiment of the invention, low amplitude signals are biased slightly higher to improve repeatability and linearity of flow versus the driving signal. The force applied to the piston **102** by the windings **104** is inversely proportional to the distance from the windings to the piston. At low signal levels, the piston does not get very close to the windings and small changes in the friction and inertia of the piston will produce significant changes in the resulting piston stroke and flow. A bias voltage is applied to bring the resting-position of the piston closer to the windings, so that small changes in the controller signal that drives the piston dominate the frictional forces and the inertia of the piston. For example, the bias voltage added to the signal is highest at the lowest driving signal (10% signal in fig. 3) and may drop to zero before the drive signal reaches 50%. The bias is reduced at higher flow levels to take advantage of the full pump stroke.

In another embodiment of the invention, the controller signal that drives the pump is a pulse-width-modulated ("PWM") direct current ("DC") voltage signal. Fig. 4 shows an exemplary DC waveform that may be used to drive the pump. Circuitry to generate the PWM DC signal in fig. 4 is well known in the art. Three different drive signals are plotted versus time. These signal modulations correspond to 10%, 50% and 90% duty cycles, which are shown for purposes of illustration and not for limitation. Applying the rectangular wave voltages of fig. 4 to the windings **104** of fig. 2 will cause the piston **102** to move to the left and compress the spring **106**. The stroke and, therefore, the flow will be roughly proportional to the voltage times the duration of the signal. The lower signals, 10% and 50%, include bias voltages between signal pulses. As in the case of the AC drive signal, the bias voltage moves the piston closer to the windings to provide greater piston response to small changes in the signal and overcome the frictional and inertia forces of the piston. This bias voltage may be varied with the duration of the drive signal. The bias voltage is highest at the minimum drive signal duration and may drop to zero before the drive voltage pulse duty cycle reaches 50%.

Other embodiments of the invention may use different controller signal waveforms to drive the piston. Use of all such controller waveforms is within the scope of the present invention as defined in the appended claims. In another embodiment of the invention, the piston pump of fig. 2 can be driven without the bias voltages shown in figures 3 and 4.

In another embodiment of the invention, both the frequency and the duration of the PWM DC controller signal modulating the pump can be varied to linearize the flow through the pump with changes in the driving signal.

In a further embodiment of the invention, pump **14** is a diaphragm pump as shown in fig. 5. In the diaphragm pump, one or more solenoidal coils **200** drive the shaft of the pump **202** back and forth. The shaft **202** deflects two diaphragms **204** that alternatively pull gas into the chambers **212** and then expel it. The two wire coil is driven with an AC signal connected to wires **(234, 236)** that drives the piston **202** back and forth by reversing the flow of current through the coil **200**. The solenoid has a permanent magnet so that a reversing magnetic field can drive the solenoid in opposite directions. The pumping force on the two chambers **212** is phased 180 degrees apart so that as one chamber is filled, the companion chamber is emptied. Check valves **208** upstream of the pumping chambers **212** allow gas flow in, while the downstream valves **210** allow flow out of the chambers and into the receiver volume **216**. The solenoidal coil **200** can be driven with a full wave AC signal. In similar fashion to the piston pump, varying the amplitude of the AC signal will vary the stroke and, therefore, the fuel flow through the diaphragm pump.

In another embodiment of the invention, the electrical coil **200** in the diaphragm pump **14** of fig 5 can be center-tapped by adding a third wire **232** to the center of the coil **200**. Wires **(234 & 236)** connect to each end of the coil. This three wire connection allows the piston **202** to be driven back and forth with a DC source. The DC source connects to the center wire **232** and the other connecting wires **(234 & 236)** are alternately connected to ground or a negative voltage, causing current to flow in one half-coil or the other.

A three-wire coil **302** and devices **(304, 306, 308)** to control the DC current flow to the coil are shown schematically in fig. 6. The coil may be used to drive a diaphragm pump solenoid, as in fig. 5. Devices **(304, 306, 308)** may be relays, field effect transistors ("FET"), bipolar transistors or other similar devices. The controller can vary the flow of fuel through the diaphragm pump by varying the amplitude of applied DC voltage signal **312** using device **304**. Devices **306, 308** can be driven as shown in fig. 7A, where first one device is closed,

then opened and then the other device is closed and then opened. The vertical axis of the figure corresponds to a normalized driving voltage, where a signal equal to "1" means a device is closed (i.e., shorted). Control strategies using PWM signals, as illustrated in fig. 4, albeit without the bias described previously for the piston pump and with suitable phasing, can be applied to each of devices **306, 308** in fig. 6.

In another embodiment of the invention, the amplitude and frequency of the diaphragm pump stroke of fig. 5 can be controlled using the three devices **(302, 304, 306)** shown in figure 6. The amplitude of the pump stroke is controlled by the average voltage at wire **312**. This voltage can be modulated by fast pulse-width-modulating device **304**. The stroke frequency may be controlled as before by devices **306** and **308**. Alternatively, device **304** can be eliminated and switches **306** and **308** can be pulse-width modulated at a high frequency during their "on" state, as illustrated in fig. 7B. In other embodiments of the invention, the center-tapped coil can be replaced by a full bridge or a half-bridge, as known to those skilled in the art.

In other embodiments of the invention, for use in applications where a constant flow of fuel is important, a filter **801** may be added between pump **800** and burner head **806**, where the fuel is mixed with the combustion air, as shown in figure 8A. One embodiment of the filter **801** is an RC filter comprising a capacitance (volume) **802** and an orifice **804**. The volume and orifice are sized to allow the required fuel flow and reduce fluctuations in flow to a desired level. Mathematical techniques that are well known in the art may be used to determine these filter parameters.

An acoustic filter using a volume and an orifice restrictor has the electrical circuit analog shown in fig. 8B. The analog of gas flow is electrical current, the analog of gas pressure is electrical voltage, the analog of volume is electrical capacitance, the analog of flow resistance is electrical resistance and the analog of gas inertia is electrical inductance. The orifice restrictor does not translate directly into this model because the orifice flow resistance is proportional to the gas flow squared (non-linear) instead of being proportional to the gas flow as the model suggests. The model can be used through the process of linearization of flow resistance for small signals. The pump gas flow ripple is attenuated by the factor of $1/(1+2\pi fRC)$. Where "f" is the frequency component of the gas flow entering the filter from the pump. Due to the orifice restrictor non- linear characteristics, the acoustic filter has a lower attenuation at low flow causing a high burner flow ripple as a percentage of

average flow. The higher ripple can cause flame instability and higher emissions of pollutants. This non-linearity also causes a high resistance to average gas flow at the higher flow rates reducing the pump maximum flow capability.

The addition of a long thin tube to the acoustic filter provides ripple attenuation through the gas mass acceleration, as shown in fig. 8C. The diagram for the electrical analog is shown in fig. 8D. The pump gas flow ripple is attenuated by the factor of $1/[1+(LC)(2\pi f)^2]$. Since L and C are not a function of flow, the filter attenuation is not affected by the flow rate and does not have the disadvantages of the filter of fig. 8A. Attenuation of the ripple also increases the pump's flow rate.

Referring again to fig. 1, in another embodiment of the present invention, controller **34** modulates the output of fuel pump **14** to control the temperature of the heater tubes **26** of the engine. The temperature of the heater tube **26** may be measured with a temperature sensor **54**, such as a thermocouple, that is attached to a heater tube **26**. When the engine increases speed, the engine draws more thermal energy from the heater tubes **26.** The tubes cool and the thermocouple **54** reports this temperature drop to the controller **34**, which in turn increases the fuel flow until the measured temperature is restored to a specified level. Any of the devices and methods for metering the fuel through the fuel pump, as described above, may be employed in this embodiment of the invention. Various fuel pump types including rotary vane pumps, piezoelectric pumps, crank driven piston pumps, etc., may be employed. In other embodiments of the invention, various operating parameters of a system, of which the pressurized chamber is a part, may be controlled by controlling the fuel pump to meter the fuel flow to the chamber. For example, the speed of an internal combustion engine or the power output of an engine may be determined by the controller. Alternatively, a fuel/air mixture ratio to a burner may be maintained by the controller.

The devices and methods described herein may be applied in other applications besides an engine, in terms of which the invention has been described. Any system which includes a pressurized combustion chamber may employ embodiments of the invention to control the flow of fuel and, thus, the rate of combustion. The described embodiments of the invention are intended to be merely exemplary and numerous variations and modifications will be apparent to those skilled in the art. All such variations and modifications are intended to be within the scope of the present invention as defined in the appended claims.